NEAR SHOEMAKER'S LOW ALTITUDE OPERATIONS AT EROS

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ABSTRACT –*After NASA's Near Earth Asteroid Rendezvous Shoemaker (NEAR) spacecraft completed its primary science objectives at 433 Eros, and the dynamical environment surrounding Eros had been characterized, plans were made to obtain close range observations (< 7 km) of the asteroid's surface towards the end of NEAR's mission and eventually land the spacecraft on Eros. The first close flyby orbit was achieved on October 26, 2000 when the NEAR spacecraft safely flew within a distance of 5.5 km near the 0° longitude (long) end of Eros' elongated body. This flyby was significant not only because it was the closest any spacecraft had ever flown past an asteroid, but also because it demonstrated the theory that a flyby of an ellipsoidal asteroid's trailing edge would increase the spacecraft's orbital energy. Several close flybys of the ends of Eros were then executed in late January 2001 by placing the spacecraft into a tight retrograde 36 x 22 km orbit. To finish this close flyby phase, a small maneuver was then executed near apoapsis to dip the spacecraft even closer to the surface upon the next periapsis passage. On January 28, 2001, NEAR Shoemaker broke its prior close flyby records of 4 – 6 km and flew within 2.7 km of the asteroid's surface enabling imaging resolutions less than 50 cm/pixel. A total of 13 low flybys were performed with altitudes under 7 km. This paper discusses the design, execution and results of NEAR's low altitude operations at Eros.*

KEYWORDS: *NEAR, Eros, low altitude, asteroid, small bodies, landing, spacecraft dynamics, orbit determination, trajectory design, gravity assist*

INTRODUCTION

On February 14, 2000, NASA's Near Earth Asteroid Rendezvous Shoemaker (NEAR) spacecraft inserted into orbit around 433 Eros becoming the first spacecraft to orbit an asteroid. The primary objectives of the NEAR mission were to obtain unprecedented close-up physical and geological observations of a near-Earth asteroid by operating the spacecraft (S/C) in orbit around it for one year. The NEAR mission was operated by the Johns Hopkins University Applied Physics Laboratory (APL), while navigation of the spacecraft was provided by the California Institute of Technology Jet Propulsion Laboratory (JPL). Orbital operations at Eros began after the Orbit Insertion Maneuver (OIM) placed NEAR into a 323 x 367 km orbit. During the first five months at Eros, NEAR progressively entered into lower circular orbits through a series of Orbital Correction Maneuvers (OCMs). NEAR's orbital radius was sequentially reduced to 200 km, 100 km, 50 km and finally 35 km as knowledge of the physical parameters of Eros were being steadily improved. Several tracking data types such as DSN radio metric tracking data, onboard optical imaging of landmarks on Eros and from the NEAR Laser Ranging (NLR) instrument supported navigation during this orbit phase. The navigational results for this portion of NEAR's successful mission are described by Williams, *et al.* [1, 2].

After nearly 8 months of orbiting the irregularly shaped Eros at distances ranging from 367 to 34 km, the dynamical environment of Eros including its mass, gravity distribution, shape, pole direction and spin had been well characterized [3]. Plans were then begun to enhance the science return by obtaining very close observations (< 7 km) of Eros' surface towards the end of NEAR's mission and eventually land the spacecraft on Eros [4, 5, 6]. To prepare for these end-of-mission (EOM) operations, a close flyby orbit was designed and executed on October 26, 2000. The S/C safely flew within a distance of 5.5 km near the 0°longitude end of Eros. This flyby was significant not only because it was the closest any spacecraft had ever flown past an asteroid, but also because it demonstrated the theory that a flyby of an ellipsoidal asteroid's trailing edge would increase the spacecraft's orbital energy [4, 7, 8]. The EOM operations included several close flybys of the ends of Eros during four consecutive days near the end of January 2001. This close flyby phase produced 12 flybys with altitudes less than 7 km. January 28, 2001 marked the end of this phase when NEAR Shoemaker broke its prior close flyby records and flew within 2.7 km of the asteroid's surface enabling imaging resolutions less than 50 cm/pixel. With this close flyby phase over, final preparations for landing NEAR Shoemaker on Eros had begun by placing the spacecraft into a relatively benign 35 km equatorial orbit for nearly 2 weeks prior to touchdown. Finally, on February 12, 2001 after a 4.5 hour controlled descent using five open-loop maneuvers, the NEAR Shoemaker spacecraft safely landed on the surface of Eros becoming the first spacecraft ever to touchdown on an asteroid. This landing was made extraordinary by the fact that the spacecraft was not designed for landing and it remained in contact with NASA's Deep Space Network after the landing. The details of navigating the S/C during NEAR's low altitude operations will be discussed in this paper. An extensive report on the design and navigation of NEAR's landing is given in ref[6].

Determination of Eros Physical Properties

It was important to have a precise knowledge of the dynamical environment encompassing Eros before attempting the low altitude flybys or the landing on the asteroid. This dynamical environment includes Eros' mass, gravity distribution, shape, pole direction and spin. It was also imperative to have an understanding of how this environment influenced NEAR's orbit, especially at close range. Close to a distended body such as Eros as described by Scheeres[7] and Scheeres *et al.* [8], the orbital dynamics of the S/C are subject to strong perturbations from the gravity field, the major contribution coming from the 2nd degree and order gravity field, which can be reduced to the two terms C_{20} (oblateness) and J_{22} (ellipticity, $J_{22} = \sqrt{C_{22}^2 + S_{22}^2}$). At low altitudes, the strong perturbations from the irregular gravity field of Eros cause large changes to the S/C orbit characteristics. These effects can lead to unstable situations where the S/C is suddenly placed on either an escape or impact trajectory.

Table 1: Eros Physical Parameters

Parameter	Value
Gravitational parameter, μ	$(4.4631 \pm 0.0003) \times 10^{-4} \text{km}^3/\text{s}^2$
Pole Direction	
Right Ascension	11.369 ± 0.003 deg
Declination	17.227 ± 0.006 deg
Spin rate	1639.38922 ± 0.0002 deg/day
Prime Meridian	326.06 deg (J2000 epoch)
Principal Axis, x	9.29 deg East
Gravity Harmonics (normalized)	
C_{20}	-0.052478 ± 0.000051
C_{21}	0.0
S_{21}	0.0
C_{22}	0.82483 ± 0.000061
S_{22}	0.027909 ± 0.000035
Reference Radius, r_o	16 km

After nearly 8 months of orbiting the irregularly shaped Eros at distances ranging from 367 to 34 km, Eros' physical parameters have been well characterized through the orbit determination (OD) process using a combination of the radio metric, landmark and NLR data[3]. Miller *et al.* [3] describe the various procedures and analyses that went into the determination of the parameters presented in Table 1.

Gravity Modeling

The successful close flybys and subsequent landing were dependent upon a correct evaluation of the gravitational acceleration of the S/C at close range. In order to prepare for NEAR's low altitude operatiions, and at the Nav Team's request, a circular 35 km polar orbit was flown in July of 2000 to globally map the gravity of Eros at high resolution. The S/C's activities were reduced for 4 out of 10 days during this orbit to eliminate the possibilities of unmodeled perturbations on the S/C. This 35 km orbit enabled a fairly accurate determination of the spherical harmonic gravity field down to degree and order 10 [3].

Because of the asteroid's irregular shape, it has been known that the spherical harmonic representation of the gravity potential is deficient at locations closer than the largest triaxial dimension. These deficiencies are due to the divergence of the harmonic expansion series inside the circumscribing sphere about the asteroid centered at its center of mass [10]. Care must be given when numerically integrating the spacecraft orbit within these regions as the spherical harmonic gravity model could lead to erroneous results. The close flyby trajectories discussed in this paper were not designed to enter this sphere. The landing, however, required the use of the polygravity model [6].

Shape Models

Based on the accurately determined Eros-relative S/C positions ($r \approx \pm 20$ m, 1-σ) within the circular 35 to 50 km orbits, the NLR data was incorporated using an off-line method to compute the high fidelity shape model shown in Figure 1. A spherical harmonic representation of the asteroid shape was determined to degree and order 34. This model was then tessellated into 17788 small triangular surface elements each including three of the 8896 vertices found on the spherical harmonic surface. The global rms error of this shape model was approximately 50 m. NLR measurements from highly sloped regions had greater errors. This model was used to measure the S/C's altitude during the low altitude flybys and the landing as well as Eros' gravity below the spherical harmonic limit.

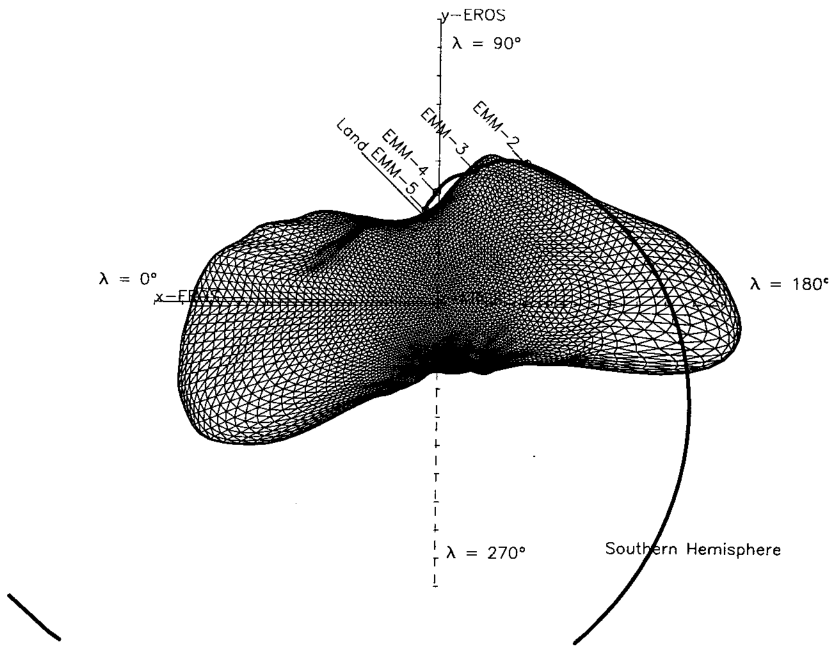

Figure 1: The 34 x 34 shape model used for the polygravity and altitude computations. A portion of the descent trajectory in the Eros body-fixed frame is shown along with locations of the braking maneuvers, EMM-2–5, and the nominal landing site (see ref[6]).

Mission Constraints

All of the NEAR S/C subsystems and the on-board instruments are fixed to the S/C bus. Two-way, coherent X-Band Doppler and range tracking data were transponded over either NEAR's High Gain Antenna (HGA), fan-beam antenna (FBA) or low gain antenna (LGA). The HGA required Earth pointing within approximately 1° and was used mainly for the transmission of science telemetry. The 40° wedged radiation pattern of the FBA allowed the S/C to remain in Earth contact during most of the orbit phase and a portion of the landing phase while the HGA could not be pointed directly toward the Earth. Science instruments point out the side of the S/C bus 90°to the solar array normal vector, so in order to obtain observations at non-terminator locations on the asteroid, the S/C's attitude must be adjusted accordingly while maintaining the requirements for solar lumination (solar incidence angle of 30° to 46° on the solar arrays and telecommunications. The maximum telecom downlink rate was achieved by continuously pointing the HGA towards Earth.

Tracking Requirements

In order to achieve fairly accurate predictions of NEAR's orbit for planning, near continuous X-Band Doppler coverage was required from the DSN's 34 m and 70 m antennas during the close flyby phase. The 70 m antennas allow the highest data return. Optical landmark tracking of known crater locations using the spacecraft Multi-Spectral Imager (MSI) was also required during the orbit phase and during the time leading up to the landing. Optical landmark tracking data was a critical component in quickly determining the post-maneuver and post-flyby trajectories. An explanation on the landmark processing is given by Owen *et al.* [11] who had acquired a database of over 10,000 landmarks on Eros. The Doppler data was very sensitive to the dynamical interaction of Eros' gravitational attraction upon the S/C. The landmark tracking complimented the Doppler by fixing the orbit of NEAR relative to Eros' spin and principal axes, which was important for determining

Eros' physical parameters. NEAR's laser ranging (NLR) data from the S/C to the surface of Eros was another important data type; this data was used for shape modeling, but not for operational navigation.

Close Flyby Orbits

The October 26, 2000 Low Altitude Flyby

During most of the Eros orbit phase, the spacecraft orbited the asteroid within a few degrees of the Sun plane-of-sky frame (SPS) (plane centered at Eros and perpendicular to the Eros-sun line). Nearly all of the mission's science objectives could be obtained in this orientation. The goals of the Near Infrared Spectrograph (NIS) instrument, however, required observing the asteroid at very low phase angles which could be obtained by flying the spacecraft between the sun and the asteroid in a zero-phase fly-over orbit. A portion of the orbit phase in October 2000 was to be devoted in obtaining these objectives [9]. Having achieved a zero-phase flyover over the north polar regions during rendezvous prior to orbit insertion, the plans were designed to perform a zero-phase flyover of the south polar region. After the failure of the NIS instrument in May 2000, NEAR's Mission Director, Bob Farquhar and the Navigation Team, suggested substituting a close flyby of the asteroid's surface in place of the zero-phase flyover to prepare for EOM operations.

To avoid unnecessary risks, the mission requirements placed on the October flyby design were to flyby the asteroid once above the sphere encompassing Eros (17.6 km) at a distance of 5 – 6 km over the sunlit surface of Eros, keep the S/C out of shadow so as to avoid relying on the potentially catastrophic battery power, target the post-flyby apoapsis at or above the pre-flyby apoapsis, and the minimize propellant usage.

After the execution of the OCM-16 maneuver, this first close flyby orbit was designed to fly within a distance of 5.5 km near the 0°longitude (long) end of Eros' elongated body on October 26, 2001. It was desirable to keep the nadir viewing geometry at closest approach (C/A) to be within the sunlit portion of Eros' surface. However, it was difficult to guarantee this due to the geometry of the pre-close flyby orbit, in the SPS frame ($i_{SPS} = 166°$) and with respect to the Eros equator ($i_{Eros} = 133°$). The basic technique for the close flyby was to place the spacecraft in an eccentric 51 X 19.2 km orbit with true anomaly and periapsis oriented so that the spacecraft would fly over an 'end' of Eros at the proper time. To keep the flyby simple, a Hohmann-type transfer orbit (true anomaly of 180°) was used to target periapsis longitude, λ_f. Targeting a C/A in the sunlit regions required performing OCM-16 before the longitude of the descending node, Ω_D, in the body-fixed frame. Earlier designs based on a few weeks of orbit predictions depended on a transfer time of nearly 2 Eros revolutions in the Eros body-fixed frame which rotates at 5.27 hours per revolution inertially. In this case, the starting longitude location, λ_o, would be the same as the periapsis longitude, but the periapsis latitude would be roughly the negative of the starting latitude. To first order, the starting longitude would be

$$\lambda_o \approx \lambda_f - P\dot{\omega}_{Eros}/2 - \pi \tag{1}$$

where P is the transfer orbit period, and $\dot{\omega}_{Eros}$ is the Eros rotation rate. The irregular gravity of Eros made the consistent targeting of the C/A and post-flyby orbit conditions challenging. The time and ΔV vector of OCM-16, had to be found through an iterative process since no software existed to reliably target the C/A conditions. As the pre-OCM-16 orbit conditions changed leading up to the final design, the starting body-fixed longitude had to be reduced by 1/3 Eros revolution to keep the same flyby geometry and time. The resultant nadir surface location was very close to the terminator. To guard against post-OCM-16 trajectory errors, the MSI observations were targeted away from the terminator, the actual closest imaging distance to the surface was 6.2 km (60 cm/pixel resolution).

Borrowing from the orbit dynamic theories of S/C motion about small bodies in ref[7, 8], the trajectory was designed to perform a 'gravity assist' over the trailing edge of Eros, thereby increasing the S/C's orbital energy, and raising the post-flyby apoapsis by 10 km or more. As discussed in ref [4], it was preferred to fly by a trailing edge of the asteroid rather than a leading edge. In general, the apoapsis radius is increased after a trailing edge flyby and decreased following a leading edge flyby. This technique was incorporated to add some safety margin by increasing the time of the next periapsis. Since this orbit was unstable by design, the S/C's safety could be in danger if the S/C were left in the resulting orbit. Therefore, after the flyby, the OCM-17 maneuver was designed to take place at the subsequent apoapsis to divert the S/C from another close approach. The timing and accuracy of the OCM-16 maneuver to initiate the flyby was critical to achieve the desired flyby location and the post-flyby orbital conditions at the time of OCM-17. To achieve the best maneuver accuracy, OCM-16 was performed by aligning the ΔV with +xA thrusters which where considered to be the best calibrated thruster set [12]. Because of the limited time between the pre- and post-flyby maneuvers, OCM-17 was preprogrammed onboard the S/C. Provisions for a late update to the time and ΔV vector for OCM-17 was provided in the schedule to account for post-OCM-16 orbit conditions. It was later found that a similar altitude flyby of the other end of Eros (180°E. Longitude) would have increased the post-flyby apoapsis radius by 40 km, but this design was discovered too late to adopt.

A Monte Carlo analysis of the October flyby was performed by generating 200 samples from simulations of the maneuver to target the flyby (OCM-16) using both expected and extreme execution errors. Expected execution errors were 1% magnitude overburn (bias) and 1% over in each component (pointing), and extreme execution errors were 20% magnitude overburn (bias) and 10% over in each component (pointing). Neither set of assumptions resulted in an impact trajectory, and the worst case from this set (extreme errors) had a minimum flyby altitude of 277 m, so the flyby was deemed relatively low risk.

A series of OCMs targeting the flyby began on October 13 with OCM-14, which lowered periapsis from the 100 x 100 km orbit to about 50 km. This was followed by OCM-15, which circularized the orbit at 50 x 50 km on October 20. Then approximately 2 days before OCM-16 (at Oct 24, 0 SCET-UTC) the S/C went into an Earth safe-mode because the onboard predicted S/C ephemeris had expired due to an operational error. The S/C was quickly returned to its pre-flyby state within a few hours. Finally, the close flyby of Eros surface was then initiated with OCM-16 ($\Delta V = 0.76$ m/s) on October 25, 2000 at 22:10 Spacecraft Event Time (SCET)-UTC. This burn was fairly accurate with an slight underburn of -0.25% and 0.33°pointing error. The periapsis occurred on October 26, 2001 at 07:01 SCET-UTC at a distance of 19.153 km. Due to the asteroid's irregular shape, however, the actual C/A point to Eros' surface happened approximately 6 minutes earlier, at 06:55 SCET-UTC with a minimum altitude of 5.457 ±0.020 km. The nadir location of this C/A on Eros was -21.52°Latitude, 328.8°E. Longitude. The S/C spent nearly 11 minutes under 6 km from the surface of Eros. The OCM-17 maneuver executed approximately 20 hours after OCM-16.

The delivery schedule for OCM-14 through OCM-17 was designed to adapt to changes caused by execution errors in each of those burns. Beginning about October 9, the predicted time of closest approach was varying up to 20 min. This was compensated by the late update on Oct. 26 at 07:00 UTC for OCM-17, just 10 hours and 40 minutes before the maneuver execution time. In addition to 2-way Doppler data, two sets of optical navigation landmarks were delivered 4 and 6 hours after OCM-16 to provide a late update tweak to the OCM-17 maneuver. Due to the planned C/A science observations, there was a known outage of 2-way Doppler data from approximately 3.5 hours before C/A to 2.5 hours after C/A because the S/C's attitude precluded telecommunications with the DSN. The first optical navigation set failed to acquire any usable landmarks. The updates design for OCM-17 changed the pointing by 10.5°and increased the ΔV magnitude by 0.7%. OCM-17 (ΔV = 1.66 m/s) occurred at the apoapsis nearly 9 hours after the flyby, to bring the S/C out of danger and place NEAR into a 64 x 200 km orbit. This maneuver was less accurate as expected with a pointing error of 1.7°and overburn of 0.8%. Afterwards, the nominal mission plan resumed with OCM-18 on November 3rd which placed the S/C into a circular 200 km orbit. The total ΔV expenditure for this flyby including OCMs 14 – 18 was 3.2 m/s. This close flyby turned out to be an actual ΔV savings of over 2 m/s over the NIS zero-phase flyby orbit [9].

Figures 2 and 3 show the trajectory of the October 26, flyby , respectively in the SPS and Eros body-fixed coordinate frames. The changes in the osculating orbital parameters due to the trailing edge flyby are shown in Figure 4. The increase in the S/C's orbital energy is evident by observing the change in the orbit osculating semi-major axis which increased from 35 km to 41 km after the flyby in Figure 4.d. As shown in Figure 4.a, the S/C's apoapsis radius increased from 52 to 64 km. The eccentricity in Figure 4.b, changed from 0.45 to 0.56. Also, as represented by the inclination of the orbit with respect to Eros' equator in Figure 4.c, the direction of the angular momentum vector, change by 2°. This energy change is approximately equivalent to a ΔV of 1.4 m/s at periapsis. Figure 5 profiles the altitude of the S/C during the close flyby. As shown in this plot, a 11 km flyby of the opposite end occurred at 30°Latitude, 198°E. Longitude. Although, this was closer than any altitude reached during the nominal mission, Eros' surface was in total darkness so imaging was precluded. Table 2 lists the conditions of the October 26 minimum altitude flybys.

The January 24 – 29, 2001 Close Flyby Phase

After the main science goals of the mission had been met and the navigation models and experience had been tuned, the EOM operations began with the close flyby phase in late January 2001. The close flyby phase consisted of performing several close flybys of the ends of Eros during four consecutive days, January 24 – 28, 2001. This phase came at the end of a long interval of 35 x 35 km retrograde equatorial orbits that began on December 13, 2000. These low orbits were designed to meet the X-ray, Gamma-ray spectrometer (XGRS) viewing requirements. An aggressive plan was laid out to include several close flybys; some were designed to fly through the saddle regions with altitudes of 1 – 2 km. The planning of this close low flyby phase had been performed in conjunction with designing the landing [6]. Based on tank pressures and blow-down curves, a lower limit of the amount of fuel available for the EOM plans was approximately equivalent to ΔV of 32 m/s. Depending on how the low flybys were designed, a large amount of fuel could be spent recovering from a flyby that increased the S/C's orbital energy significantly as did some of the saddle flyby designs. Due to the large work schedule that was necessary for the design and navigation of both the close flyby and landing phases, the NEAR project decided to keep this close flyby phase as simple as possible.

To simplify the planning of the close flyby orbits, no special surface locations were targeted. The spacecraft was placed into an elliptical 36 km x 22 km equatorial orbit (retrograde) on January 24, 2001 with a 0.54 m/s OCM-21 maneuver. During this time the orientation of the south pole of Eros was nearly aligned with Eros-sun direction vector. This meant that the southern hemisphere of Eros was continuously sunlit while the northern portion was in constant darkness. The nadir surface imaging observations were constrained to lie along the terminator. The advantage of this orbit, however, was that it allowed the possibility of two close flybys ranging from 4.4 – 7 km, one

Table 2: Close Flyby Altitudes

SCET-ET	Radius (km)	Altitude (km)	Latitude (deg)	E.Longitude (deg)	V_{Body} (m/s)
26-OCT-2000 06:55:00	19.176	5.457	-21.540	329.020	11.15
26-OCT-2000 08:09:00	24.341	11.108	30.100	198.050	11.16
24-JAN-2001 21:56:00	27.791	9.900	-0.580	185.950	13.41
24-JAN-2001 23:54:00	22.483	6.592	-1.050	334.650	12.67
25-JAN-2001 01:10:00	22.793	4.946	0.180	187.720	12.73
25-JAN-2001 12:34:00	23.798	5.894	-0.670	186.470	12.84
25-JAN-2001 14:23:00	22.632	6.715	1.320	337.020	12.69
25-JAN-2001 15:46:00	26.192	8.333	1.270	186.290	13.15
26-JAN-2001 01:47:00	23.884	7.963	0.640	335.950	12.83
26-JAN-2001 03:06:00	22.244	4.421	1.560	185.510	12.69
26-JAN-2001 04:57:00	25.728	9.852	0.060	338.660	13.08
26-JAN-2001 14:26:00	25.869	8.009	1.270	186.450	13.11
26-JAN-2001 16:19:00	22.152	6.234	0.880	335.870	12.65
26-JAN-2001 17:37:00	23.992	6.119	-0.640	187.490	12.86
27-JAN-2001 03:39:00	26.005	10.119	1.270	334.800	13.11
27-JAN-2001 05:01:00	22.699	4.828	0.200	185.640	12.73
27-JAN-2001 06:49:00	23.699	7.828	-1.210	338.070	12.81
27-JAN-2001 08:16:00	28.141	10.252	-0.670	187.210	13.47
27-JAN-2001 16:15:00	28.315	10.431	0.680	186.540	13.50
27-JAN-2001 18:14:00	22.714	6.801	-0.940	336.090	12.70
27-JAN-2001 19:31:00	22.607	4.724	-0.970	187.270	12.71
27-JAN-2001 21:28:00	27.705	11.803	0.720	337.990	13.39
28-JAN-2001 07:17:00	28.485	10.583	-0.840	186.680	13.48
28-JAN-2001 09:14:00	20.933	5.029	-0.780	335.090	12.50
28-JAN-2001 10:25:00	20.601	2.737	0.800	187.170	12.54
28-JAN-2001 12:16:00	26.950	11.114	1.120	339.700	13.21

of each end of Eros, during each periapsis passage without placing any requirements on the time of the maneuver to initiate it. This orbit configuration was relatively stable since the dynamical interaction with the asteroid's ends are in general minimized for equatorial orbits [4, 7, 8]. What had been believed to be a relatively easy orbit design for navigation in achieving close imaging of Eros' surface actually turned out to be a difficult task since it was a challenge to produce consistent orbit predictions weeks in advance. These orbit predictions were needed by the Sequencing Team for scheduling the imaging and downloading the images on the allocated 70 meter Deep Space Network (DSN) antennas. To finish this close flyby phase, a small maneuver, OCM-22 ($\Delta V = 0.56$ m/s), was then executed near apoapsis to dip the spacecraft even closer to the surface upon the next periapsis passage with a eccentric 37 x 19.7 km orbit . On January 28, 2001, NEAR Shoemaker broke its prior close flyby records and flew within 2.7 km of the asteroid's surface enabling imaging resolutions less than 50 cm/pixel. Because this orbit was not stable and the orbital period was less than 13 hours, a post-flyby maneuver (OCM-23, $\Delta V = 0.67$ m/s) had to be preprogrammed on-board the spacecraft to circularize the orbit at the 35 km apoapsis. Figure 6 lists the segments of the close flyby phase. Subsequent to the close flyby initiation, a late update was provided for the closest flyby orbit and maneuvers OCM-22 & 23 on January 26, 2001. Again all maneuvers were desired to be exclusively performed on the +xA thrusters, but only OCM-21 & 23 could align the S/C's +xA thrusters in the ΔV direction. With the orbit update, it was necessary to tweak the OCM-22 maneuver magnitude by a rather large 39% and direction by 8.4°and the OCM-23 maneuver by -1.1% magnitude and 5.0°in pointing.

Although the design of the January close flyby orbits was simple, the reproduction of achieving the identical characteristics of the orbit was not. The sequencing of the science observations and data downlinks started with a build schedule four weeks in advance. Navigation was required to deliver 2 orbit updates per week. After fitting NEAR's orbit with latest 2-way X-Band Doppler, range and optical landmark tracking data in a square root information least-squares filter, the orbit was propagated up to four weeks ahead. Due to the orbit orientation (radius = 35 km circular, equatorial $i_{Eros} = -179°$and the attitude turns for the XGRS science observations in December of 2000, these orbits were not predicting the orbit characteristics consistently at the time of the low flyby phase initiation with OCM-21 burn on January 24, 2001. The XGRS observations were performed on half the orbit while the data was received on the other half of the orbit. Due to the requirements for the XGRS observations, the attitude during these observations precluded the reception of 2-way Doppler data on each half orbit. It was believed that this 'strobing' effect on NEAR's orbit determination was a possible cause of the unreliable predictions. Each day's worth of close observations during the low flyby phase was scheduled to be downlinked on the DSN's 70 meter antennas. Since NEAR was only able to allocate one of these stations per day, the sequence was constrained to devote part of the orbit to downlinking the data on the scheduled antennas. Each time the predicted orbit characteristics changed, the sequence fell apart. Finally, in the week before January 24, 2001, the predicted orbits began to give consistent orbit conditions. The close flyby phase maneuver magnitude and pointing errors were as follows: OCM-21, 1.4% overburn and 0.3°, OCM-22, 1.4% underburn and 0.5°, OCM-23, 0.8% and 0.3°.

Figure 7 shows a plot of the closest flyby orbit in the SPS frame. The tic marks are shown at 1 hour intervals from the OCM-21 maneuver. The 2.7 km C/A occurred approximately 9 hours after OCM-21 over the Eros surface location at 0.80°latitude & 187.17°E. longitude. The osculating orbital elements during the close flyby phase are shown in Figure 8 to be wildly fluctuating due to perturbations induced by the asteroid's irregular gravity field. The altitude variation during the closest flyby orbit is displayed along with the orbital radius in Figure 5.b. As shown in this diagram, the actual periapsis time occurred 33 minutes at a radius of 19.673 kmearlier than the C/A. Table 2 lists the 24 C/A altitudes under 12 km. Twelve of these flybys were under 7 km while a total of 5 were under 5 km altitude. Figure 9 displays the altitude and radius profile during the entire close flyby phase.

CONCLUSIONS

Several successful low flybys were performed towards the end of NEARs mission. These orbits were attempted only after the accurate determination of the Eros physical parameters including its gravity distribution, pole direction, spin rate and shape were obtained. The relatively simple design of the low flyby phase at the end of January 2001 easily produced 24 low flybys with altitudes under 12 km. A total of 13 low flybys were performed with altitudes under 7 km. Since this orbit was retrograde, near equatorial, each periapsis passage was capable of producing 2 close flybys under 12 km. Occasionally, 3 close flybys under 10 km were achieved during a periapsis passage. A relatively small maneuver completed the close flyby phase by dipping the orbit periapsis a few kilometers to achieve the closest 2.7 km flyby. Because of the inclined orbit relative to the Eros equator, the October 2000 close flyby proved to be more challenging, especially because of the incorporation of the 'gravity assist'. This flyby successfully demonstrated the theory that a flyby of an ellipsoidal asteroid's trailing edge could increase the spacecraft's orbital energy. Though these types of orbits are unstable by design, future small body missions could minimize fuel expenditure with the carfeful use of these orbits in their mission designs.

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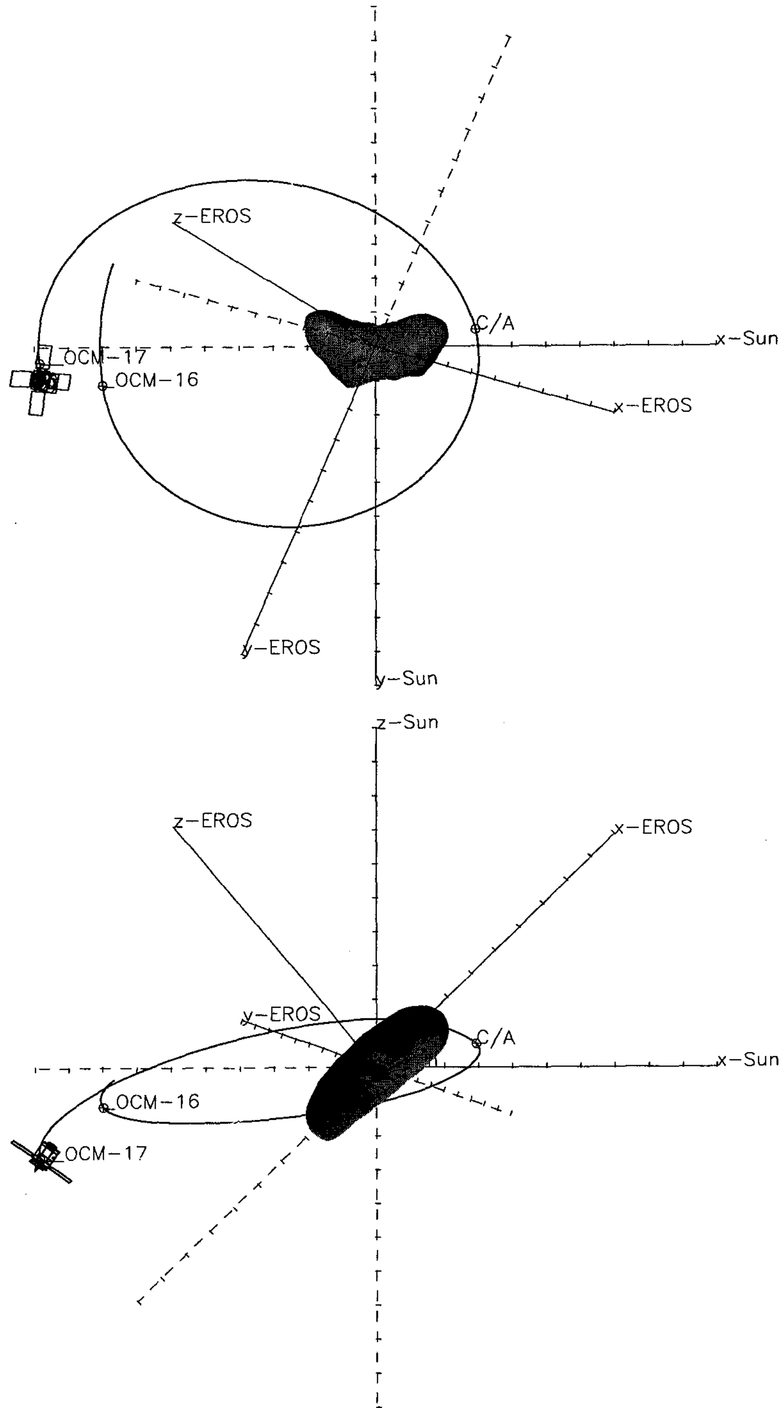


Figure 2: The October 26, 2000 Close Flyby in the SPS $x - y$ (top), and the SPS $x - z$ frames(bottom). The orientation of the asteroid is fixed at the time of C/A: 26-OCT-2001 06:55 SCET-UTC

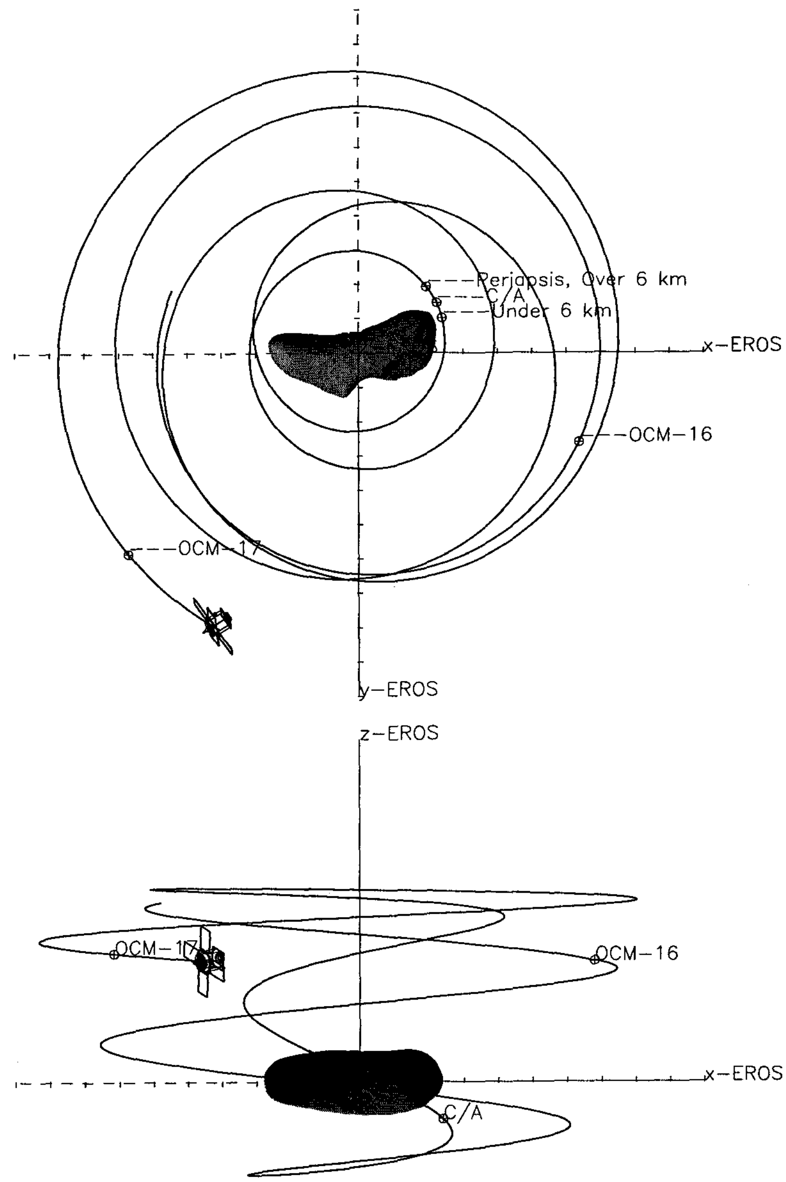
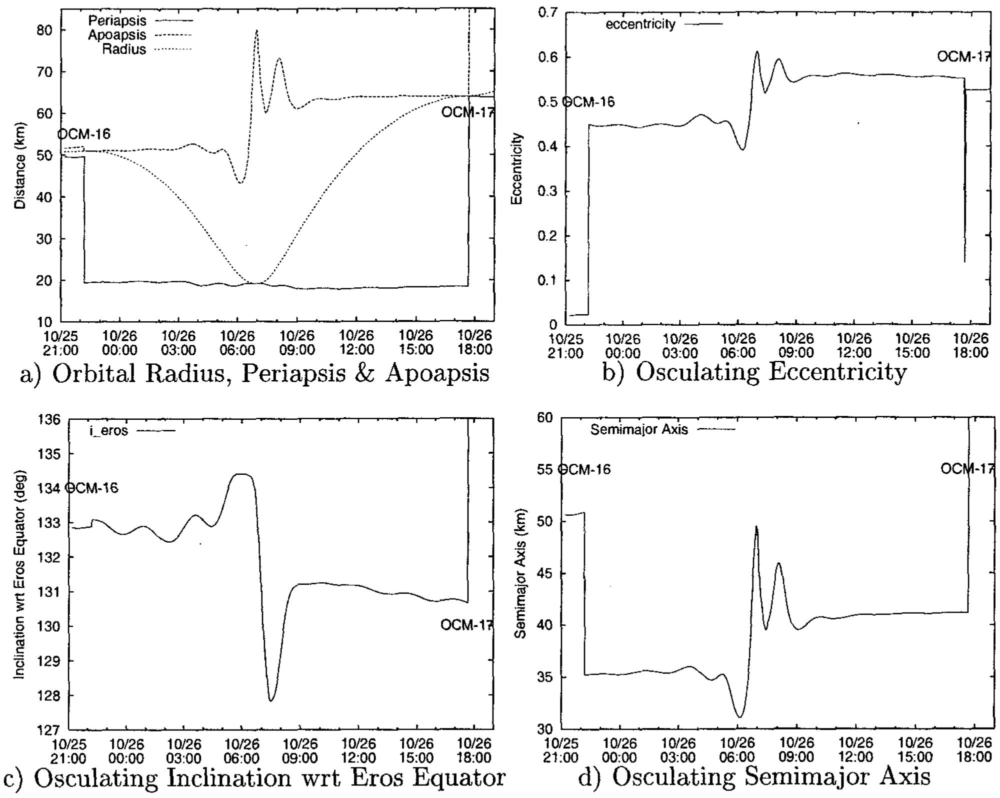


Figure 3: The October 26, 2000 Close Flyby in the Eros Body-fixed frame $x - y$ (top), and the Eros Body-fixed $x - z$ frames (bottom)



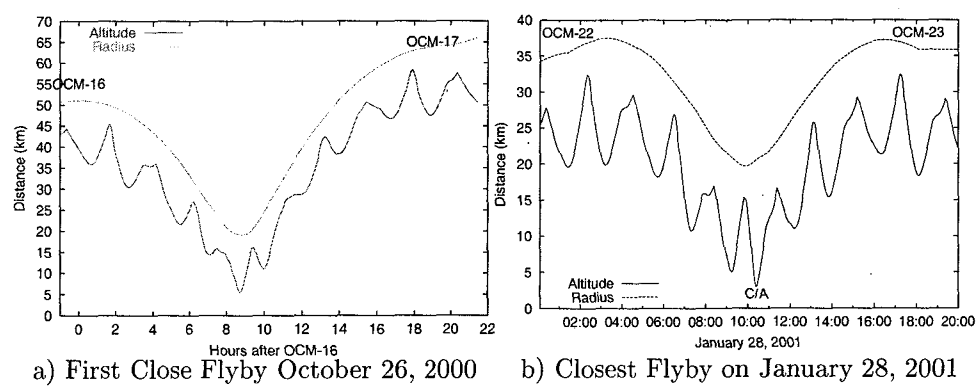
a) Orbital Radius, Periapsis & Apoapsis

b) Osculating Eccentricity

c) Osculating Inclination wrt Eros Equator

d) Osculating Semimajor Axis

Figure 4: Osculating Orbit Parameters for the October 26 close flyby orbit



a) First Close Flyby October 26, 2000

b) Closest Flyby on January 28, 2001

Figure 5: Altitude & Radius of Close Flyby Orbits

Close Flyby Phase

Phase	OCM†	Date Time§ (SCET-UTC)	DOY	Orbit (km x km)	Altitude (km)	Period (hours)	Inclination (deg) ATE‡	Inclination (deg) SPS††	Length (days)	ΔV (m/s)
Nominal Orbit	20	12/13/00 20:15	348.8	37.8 x 33.5	> 15	16.8	179	179	41.83	1.245
Close Flyby Scenario										
Low Alt Eccentric	21	1/24/01 16:05	24.7	35.6 x 21.7	4.2 -- 7 (9 low flybys)	13.33	179	177	3.39	0.534
Close Flyby 1	22	1/28/01 1:25	28.1	37.0 x 19.7	2.7 -- 5.0 (2 low flybys)	12.5	179	176	0.69	0.567
Recover	23	1/28/01 18:05	28.8	36 x 35	> 17	16.8	178	176	4.62	0.672
Orbit Trim	24	2/2/01 8:51	33.4	36 x 35	> 17	17	178	174	4.37	0.026
Orbit Trim	25	2/6/01 17:44	37.7	36 x 35	> 17	17	178	174	5.90	0.013
									Total ΔV	1.812

†OCM = Orbital Correction Maneuver

§SCET-UTC = Spacecraft Event Time (UTC)

††SPS = Sun Plane-of-Sky Coordinate Frame

‡ATE = Asteroid True Equator

Figure 6: Final Close Flyby Design Plan

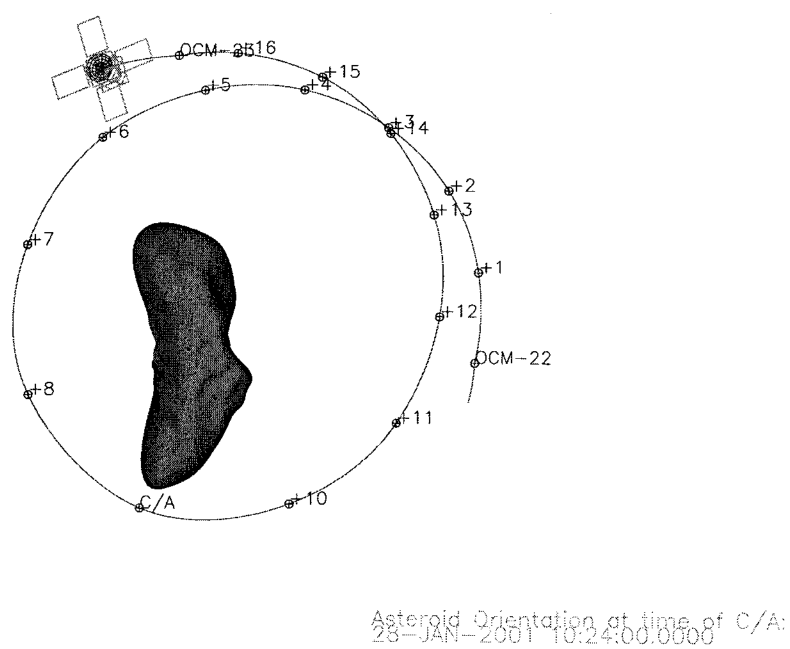
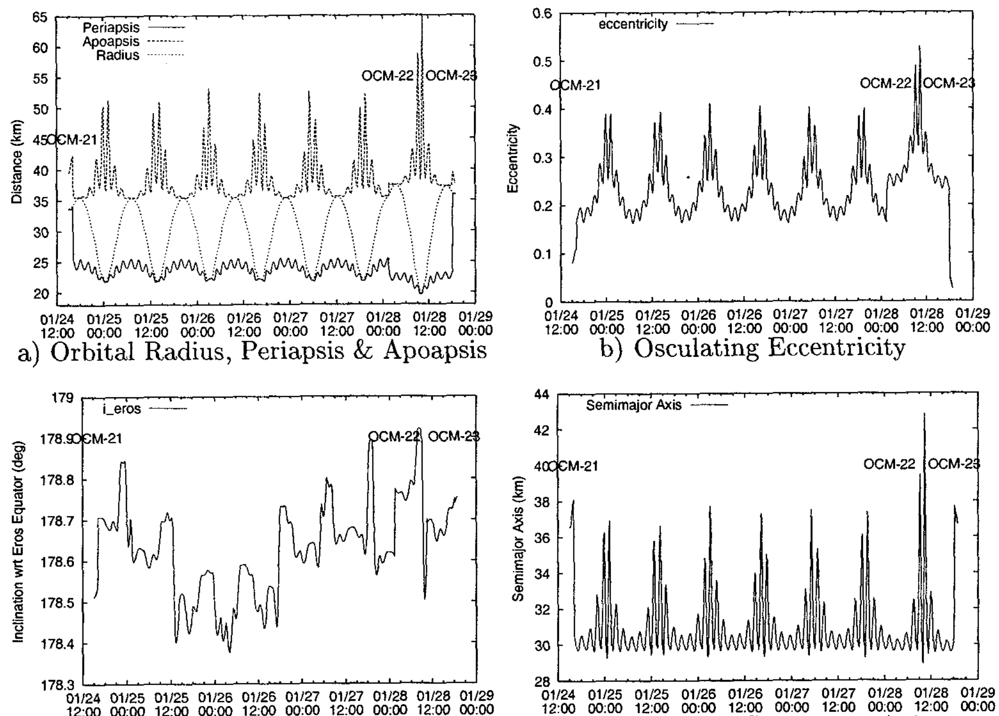


Figure 7: The Closest Flyby Orbit on January 28, 2001



a) Orbital Radius, Periapsis & Apoapsis
b) Osculating Eccentricity
c) Osculating Inclination wrt Eros Equator
d) Osculating Semimajor Axis

Figure 8: Osculating Orbit Parameters for the January 24 - 29 close flyby orbits

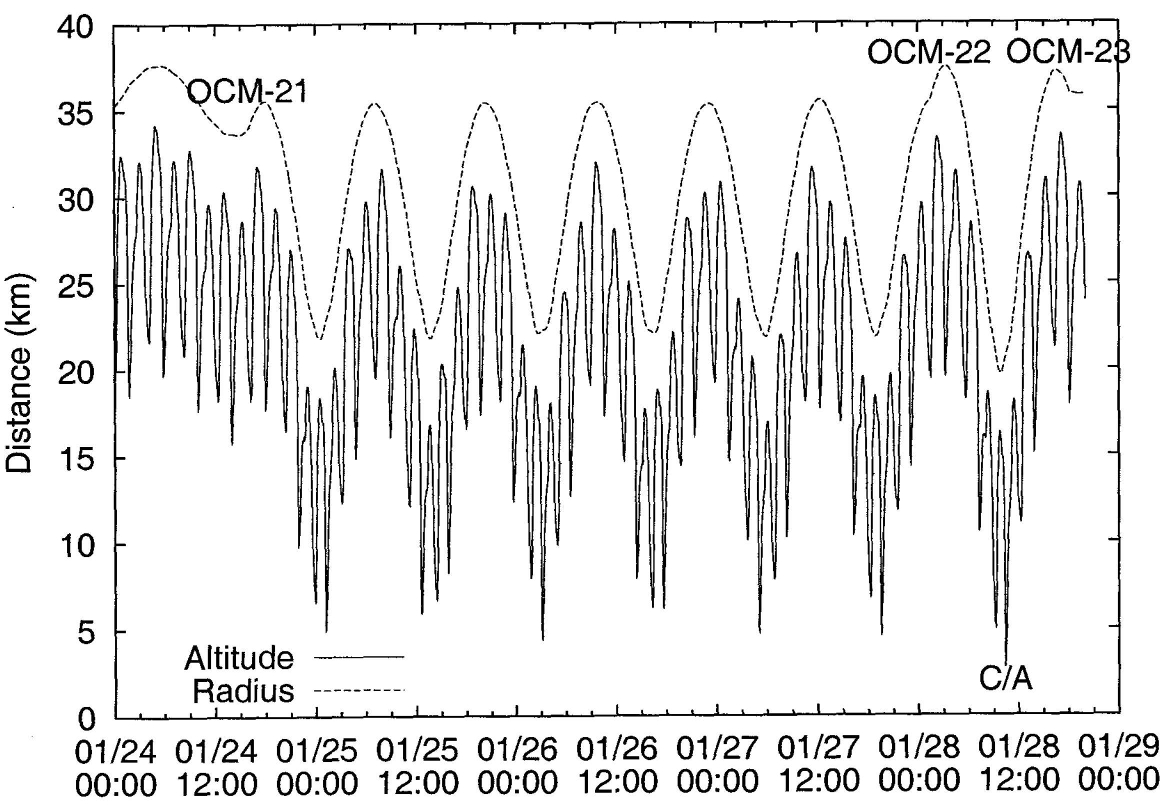


Figure 9: Altitude & Radius During the Close Flyby Phase in January 2001